

Proto-Magnetars as GRB Central Engines: Uncertainties, Limitations, & Particulars

Todd A. Thompson^{*,†}, Brian D. Metzger^{**,‡} and Niccolò Bucciantini[§]

^{*}*Department of Astronomy and Center for Cosmology & Astro-Particle Physics, The Ohio State University, Columbus, Ohio 43210; thompson@astronomy.ohio-state.edu*

[†]*Alfred P. Sloan Fellow*

^{**}*Department of Astrophysical Sciences, Peyton Hall, Princeton Univ.; Princeton, NJ 08544 USA*

[‡]*Einstein Fellow*

[§]*NORDITA, Roslagstullsbacken 23, 106 91 Stockholm, Sweden*

Abstract. The millisecond proto-magnetar model for the central engine of long-duration gamma-ray bursts is briefly reviewed. Limitations and uncertainties in the model are highlighted. A short discussion of the maximum energy, maximum duration, radiative efficiency, jet formation mechanism, late-time energy injection, and (non-)association with supernovae of millisecond magnetar-powered GRBs is provided.

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INTRODUCTION

Models for the central engine of long-duration gamma ray bursts (GRBs) are highly constrained by the character of the prompt emission and the afterglow, and — at least in some cases (and perhaps nearly all [1]) — the fact of an associated supernova (SN). A successful model must at minimum satisfy several criteria. It must generate a collimated outflow with high Lorentz factor $\gamma_\infty \gtrsim 10^2 - 10^3$ and high kinetic luminosity ($\dot{E} \sim 10^{50} - 10^{51} \text{ ergs s}^{-1}$) on a timescale of $\sim 10 - 100$ seconds. Additionally, inferences from X-ray observations by *Swift* indicate that there may be late-time energy injection by the central engine on timescales of hours to days [2].

There is little diversity among models for the central engine and essentially all can be simply classed as a rotating compact object that drives an asymmetric relativistic outflow. The two leading models are the “collapsar” and the “millisecond proto-magnetar.” The former, as described in [3] and developed in [4, 5], proposes that GRBs arise from the collapse of rapidly rotating Type-Ibc progenitors. A black hole forms with an accompanying accretion disk and drives a collimated relativistic outflow along the axis of rotation via either neutrino heating or magnetic stresses. Ref [6] have recently pointed out that rapid mass loss during rotating collapse might prevent the formation of a central black hole, at least for some time.

In contrast to the collapsar mechanism, the “millisecond proto-magnetar” model posits a newly formed rapidly rotating neutron star (spin period $P \sim 1 \text{ ms}$) with surface magnetic field of magnetar strength ($B \gtrsim 10^{15} \text{ G}$), cooling via neutrino radiation, and driving a neutrino-heated magneto-centrifugal wind [7, 8, 9]. Millisecond

proto-magnetars might be produced by rotating Type-II and Type-Ibc progenitors, the accretion-induced collapse of a white dwarf, the merger of two white dwarfs, and/or (potentially) the merger of two neutron stars [10]. Thus, they may trace both young and old stellar populations. See Refs [11, 12, 13, 14] for more on the development of this model.

Here, we briefly review the millisecond proto-magnetar model for long-duration GRBs. We then discuss some of the particulars of the model, including some of its limitations and uncertainties. A recent comparison between the collapsar and millisecond-magnetar models can be found in Ref [15].

THE BIRTH OF MILLISECOND PROTO-MAGNETARS

Core-collapse supernovae (SNe) leave behind hot proto-neutron stars that cool on the Kelvin-Helmholtz timescale ($t_{\text{KH}} \approx 10 - 100$ s) by radiating their gravitational binding energy ($\sim 10^{53.5}$ ergs) in neutrinos [16, 17]. A fraction of these neutrinos deposit their energy in the tenuous and extended atmosphere of the proto-neutron star.¹ In the standard picture, net neutrino heating drives a thermal wind that emerges into the post-SN shock environment, blowing a wind-driven bubble into the exploding and expanding SN cavity [18, 19]. A neutrino-driven wind is obtained in all successful models of SNe, regardless of how the explosion is seeded and is a natural consequence of the low-pressure cavity created by the explosion and the very high thermal pressure at the proto-neutron star surface [19, 20, 21].² For most massive stellar progenitors with extended hydrogen envelopes (Type-II), the cooling phase is over well before shock breakout at the progenitor’s surface (~ 1 hour after collapse). For compact Type-Ibc SNe, the SN shockwave traverses the progenitor on a timescale comparable to t_{KH} .

For a neutron star with $M = 1.4 M_{\odot}$, $R = 10$ km, rotation frequency Ω , and a magnetar-strength magnetic field, the mass-loss rate during t_{KH} is given by [22, 23, 7, 9]

$$\dot{M}(t) \approx 4 \times 10^{-7} L_{\nu,51.5}^{5/2}(t) \exp[\Omega(t)^2/\Omega_c^2] M_{\odot} \text{ s}^{-1}, \quad (1)$$

where $L_{\nu,51.5}(t) = L_{\nu}(t)/10^{51.5} \text{ ergs s}^{-1}$ is the total neutrino luminosity, and $L_{\nu} \propto \langle \epsilon_{\nu} \rangle^4$ has been assumed, where $\langle \epsilon_{\nu} \rangle$ is the average neutrino energy. The normalization of equation (1) and its L_{ν} dependence follow from the physics of the weak interaction and the depth of the NS gravitational potential [22, 23]. The exponential factor in equation (1) accounts for the mass loss enhancement by magneto-centrifugal forces when B and Ω are large ($\Omega_c \approx 2000 L_{\nu,51.5}^{0.08} \text{ rad s}^{-1}$ [7, 9]).

One of the most important components of the proto-magnetar model is that as the neutron star cools, $L_{\nu}(t)$ and $\langle \epsilon_{\nu} \rangle(t)$ decrease on a timescale t_{KH} . Typically, the dependence $L_{\nu}(t) \propto t^{-1}$ is found in cooling models of non-rotating non-magnetic proto-neutron stars until $t \sim 30 - 40$ s when $L_{\nu}(t)$ plummets as the neutron star becomes transparent [17]. As a result of equation (1), as $L_{\nu}(t)$ decreases, $\dot{M}(t)$ decreases. For this reason, for fixed surface magnetic field strength B , the wind becomes increasingly magnetically-dominated

¹ The charged-current interactions $\nu_e n \leftrightarrow p e^-$ and $\bar{\nu}_e p \leftrightarrow n e^+$ dominate heating and cooling.

² This statement is true even if the wind is “one-sided” in its first seconds, as in Ref [21].

and relativistic as a function of time. Like beads on a stiff wire, the matter is accelerated off of the surface of the proto-neutron star by the combined action of big B and Ω . The degree to which the magnetic field dominates the dynamics and accelerates the flow is quantified by the magnetization at the light cylinder ($R_L = c/\Omega \sim 50P_1$ km):

$$\sigma_{\text{LC}} = B^2/(4\pi\rho c^2)|_{\text{LC}} \approx 75 B_{15}^2 P_1^{-4} L_{v,51.5}^{-5/2}(t), \quad (2)$$

where $B_{15} = B/10^{15}$ G is the surface dipole field strength. The Lorentz factor of an outflow at large distances can approach $\gamma_\infty \rightarrow \sigma_{\text{LC}}$ (see Ref [24]) if there is efficient conversion of magnetic energy into kinetic energy (in which case $\sigma(r)$ itself will become small at large r). Thus, under the assumption of efficient conversion of magnetic energy to kinetic energy $\gamma_\infty(t)$ increases dramatically as \dot{M} drops on t_{KH} .

Starting from a time $t \sim 1$ s after the collapse and successful SN explosion, there are several phases in the life a proto-neutron star wind. Although the specific timing of each phase depends on B and Ω , for a millisecond magnetar they are roughly the following. For a second or so after explosion, as the proto-neutron star contracts to its final radius and spins up, the wind is pressure-dominated and driven by neutrino energy deposition. The asymptotic velocity of the flow is $\sim 0.1c$. Just a few seconds later, the wind rapidly becomes magneto-centrifugally dominated, but it is still non-relativistic ($\sigma_{\text{LC}} < 1$). Perhaps $\sim 2 - 5$ s into the cooling epoch, $\dot{M}(t)$ decreases sufficiently that $\sigma_{\text{LC}}(t)$ becomes larger than unity, the flow is accelerated to near c by magneto-centrifugal forces from the surface of the neutron star out to the light cylinder. It is this late-time outflow — deep into the cooling epoch of the magnetar, many seconds after the explosion is initiated — that is the most promising for producing a GRB. Eventually, at the end of the cooling epoch $L_v(t)$ and $\dot{M}(t)$ decrease dramatically (see Ref [17]), $\sigma(t)$ increases to $\sim 10^6$ and the magneto-hydrodynamical mass loss ceases, and the millisecond magnetar enters its “pulsar” phase in which its energy loss rate is presumed to be given by the force-free (“vacuum dipole”) spindown formula [25]

$$\dot{E}_{\text{FF}} \approx B^2 R^6 \Omega^4 / c^3. \quad (3)$$

The wind does not emerge into vacuum. It follows the preceding, SN shockwave, which propagates through the progenitor at $\sim 10,000$ km s $^{-1}$. As the wind becomes increasingly fast a few seconds after the explosion is initiated, it shocks on the slower outgoing SN shockwave. This interaction produces a wind-driven “magnetar wind nebula,” and the residual azimuthal component of the magnetic field within the cavity exerts a “pinch” force that leads to a prominent and strong jet that punches through the star [26, 27, 28]. This effect is equivalent to that discussed in Refs [29, 30]. See also [14].

UNCERTAINTIES, LIMITATIONS, & SOME PARTICULARS

Efficiency & Internal Shocks

As discussed above, $\sigma_{\text{LC}}(t)$ and (potentially) $\gamma_\infty(t)$ increases monotonically as a function of time in the proto-magnetar model. Although there may be eruptions from the magnetar surface during cooling which rapidly modulate \dot{M} and σ , the overall trend

from low σ (< 1) to high σ ($> 10^5$) on a $\sim 10 - 100$ s timescale is unavoidable. If $\sigma(t) \propto \gamma_\infty(t)$, this leads to very high radiative efficiency via internal shocks (approaching ~ 0.3 ; see Ref [10] for discussion in the context of 060614-like GRBs [31, 32]).

Jet Formation

Perhaps counter-intuitively, the models of Refs [26, 27, 28] show that the otherwise predominantly equatorial proto-magnetar wind can be efficiently converted into a jet. Importantly, these works find that little of spindown (wind) power is transferred to the “spherical” SN component of the explosion. While the slow SN shock acts to contain the wind and allow the jet to develop, a variety of simulations with different parameters (B and Ω) show that the majority of the wind power escapes along the axis of these axisymmetric relativistic MHD simulations. This property of the system preserves the overall degree of relativity of the outflow from the light cylinder to the edge of the progenitor (no spindown energy is “lost” to the quasi-spherical SN). It is then difficult to argue that the relativistic magnetar outflow acts to super-energize the SN explosion for comparison with events like SN 2003dh (GRB 030329; [33]), which may require Ni yields and ejecta velocities higher than typical Ic SNe [28].

Several theoretical questions remain: (1) What happens to the process of jet formation in 3D, when the magnetic and spin axes of the proto-magnetar may be misaligned? (2) If jet formation is indeed robust, is the alternating field (“striped” wind) configuration expected for an oblique rotator preserved along the pole in the jet? That is, is the jet stable? This issue bears critically on the efficacy of magnetic reconnection models for the jet acceleration and emission [24].

The Maximum Energy

The gravitational binding energy of a neutron star is of order $E_{\text{grav}} \sim GM^2/R \sim 5 \times 10^{53}$ ergs. For maximal rotation, one might guess that the total amount of rotational energy that can be stored in a proto-neutron star at birth is $\sim E_{\text{grav}}$, and thus that the maximum possible energy for a GRB powered by the rotational energy of a neutron star is $E_{\text{rot}} \sim E_{\text{grav}}$. However, at very rapid rotation rates we expect strong deformations of the neutron star (as in, e.g., Ref [34]), which will emit copious gravitational waves. These losses will effectively spin down the proto-magnetar. For example, taking the kinetic power in the outflow to be $\dot{E}_{\text{wind}} \sim \dot{M}R^2\Omega^2/2$ as the flow starts to become magnetically-dominated, and taking the energy loss rate in gravity waves to be $\dot{E}_{\text{GW}} = (32/5)GI^2\varepsilon^2\Omega^6/c^5$ [35], where $I = I_{45}10^{45}$ cgs is the moment of inertia and $\varepsilon = \varepsilon_{0.01}0.01$ is the ellipticity, the critical Ω above which $\dot{E}_{\text{GW}} > \dot{E}_{\text{wind}}$ is $\Omega \sim 5000\dot{M}_{-3}^{1/4}R_{10\text{km}}^{1/2}I_{45}^{-1/2}\varepsilon_{0.01}^{-1/2}$ rad s $^{-1}$, where $\dot{M}_{-3} = \dot{M}/10^{-3} \text{ M}_\odot \text{ s}^{-1}$ and $R_{10\text{km}} = R/10\text{km}$. Note that the magnetic field within the neutron star may produce non-zero ε [36, 37]. Although sophisticated models of rapidly rotating neutron star birth are required to address this question in detail, this estimate and others suggests that the magnetar can have a maximum total rotational energy of $E_{\text{max}} \sim 5 \times 10^{52}$ ergs at the time of cooling. Such a calculation is particularly relevant since recent work suggests that some GRBs may approach this bound [38, 39]. However, the inference of the total energy of the GRB depends on observation of the jet “break” in the afterglow lightcurve.

Work by Ref [40] suggests earlier calculations of the total energetics via jet breaks may overestimate the energy in the GRB jet by a factor of $\sim 3 - 4$.

A theoretical investigation of rapidly rotating 3D MHD stellar collapse is required to address the issue of E_{max} for millisecond proto-magnetars in detail. Although one might guess that there is no similar bound for the collapsar mechanism (short of the entire rest mass energy of the accreted material), Ref [6] have found that it might be difficult to promptly form very rapidly rotating black holes in stellar collapse because of rapid mass loss. Nevertheless, E_{max} remains an important potential observational probe of the GRB central engine. It is particularly interesting to speculate that observations may one day provide evidence for a well-defined maximum energy for long-duration GRBs, thus providing a crucial clue to their nature.

The Maximum Duration

Equation (2) shows that σ_{LC} (and, hence, γ_{∞}) is a strong function of L_{ν} . In turn, L_{ν} is a strong function of time in non-rotating models of proto-neutron star cooling [16, 17]. This time evolution implies that the wind quickly evolves from $\sigma \sim 1$ to $\sigma \sim 1000$ on a timescale of less than ~ 30 s. If the prompt emission mechanism requires that σ is less than some upper bound (say, 1000; see [41]), then the sharp cutoff in L_{ν} at the end of the cooling phase should quickly end the prompt emission. This implies that proto-magnetar powered prompt emission from GRBs should have a sharp temporal distribution in the rest frame (see [42]).

In the magnetar model, can the duration of the prompt emission be increased? There are potentially two ways. First, the neutrino diffusion timescale is longer for more massive NSs. For a $2 M_{\odot}$ NS, the time at which L_{ν} suddenly decreases, increases somewhat, from ~ 30 s for a 1.4 to perhaps 40 – 50 s. The second way is through rapid rotation. Although models of rapidly rotating neutron star cooling have not yet been constructed, parameterized 1D models of core-collapse SNe with rotation indicate that the overall neutrino luminosities and average energies might be decreased by a factor of at most $\sim 5 - 6$ [43]. Since, at zeroth order, the same amount of gravitational binding energy must be liberated, we expect that t_{KH} should increase by the same factor. Thus, if an upper bound on σ (or γ_{∞}) determines when the prompt emission shuts off, then the maximum duration of a long-duration GRB powered by a ms-magnetar is no longer than ~ 200 s. Observations of GRBs showing that the prompt phase lasts more than this in the rest frame would strain the magnetar model.

Flares & Late-Time Activity

At late times, after neutrino-driven mass loss from the proto-neutron star has subsided and deleptonization is complete, the energy loss rate of the magnetar should approach the force-free limit, given in equation (3). This implies that $\dot{E} \propto \Omega^4 \propto t^{-2}$. However, we know from studies of pulsars in the Galaxy that the observed braking index is $n \equiv \Omega \ddot{\Omega} / \dot{\Omega}^2 \sim 2.5 - 2.9$ (see [8], and references therein). While the cause of $n \neq 3$ braking index is unknown, this finding implies that we should expect $\dot{E} \propto t^{-2.33}$ to $\propto t^{-2.05}$ in the force-free pulsar-like phase, if newly born magnetars spin down like their less-energetic pulsar cousins. In any case, the rotational energy reservoir should

likely decrease monotonically, and this behavior should imprint itself on any emission during this phase. For this reason, the late-time flares have been analyzed by Ref [44] and [45]. The former find that the average flare luminosity declines as a powerlaw in time as $L \propto t^{-1.5 \pm 0.16}$, whereas the latter find that the peak luminosity of the flares correlates with the timescale of the peak as $L \propto t^{-2.7 \pm 0.5}$. The former is likely too shallow a time-dependence for the magnetar model if the flares are interpreted as powered by spindown [44], whereas the latter may be somewhat too steep.

Recent work by Ref [46] and [47] explicitly connect the X-ray plateaus seen in the early afterglow of many *Swift* long-duration GRBs with magnetar spindown. If this correspondence is correct, the magnetar model should predict correlations between the character of the prompt emission and the duration and flux of the plateau.

Also regarding very late-time central engine activity, it has been suggested that the discovery of a giant magnetar flare (a scaled-up version of those that occur from Galactic magnetars) associated with an old GRB afterglow in a nearby galaxy would provide a striking confirmation of the magnetar GRB model [48].

Time Evolution of the Magnetic Field

A complicating and uncertain feature of the magnetar model for GRBs is the time evolution of the magnetic field. This could be important for both the early-time and late-time evolution and emission. At early times, during the neutrino cooling phase, B may evolve because of dynamo action in the proto-magnetar during the explosion itself, or during its convective cooling phase [49, 50]. This effect could extend or shorten the prompt phase if a certain range of σ_{LC} (or γ_∞) is required for efficient emission. After the prompt phase, B might evolve in the magnetar via magnetic dissipation [51], which could potentially lead to extended late-time X-ray activity. A time-variable B would also complicate the time dependence of spindown at all phases (eq. 3).

(Non-)Association with Supernovae

Some proto-magnetars may be formed from the collapse of a Type-Ibc progenitor. In this scenario, one imagines that the SN mechanism in some form (e.g., the “neutrino mechanism” [52]) launches a SN shock with $\sim 10^{51}$ ergs that produces ^{56}Ni via explosive nucleosynthesis. This would explain the presence of an accompanying SN, but not the bright character of some GRB-SNe. If ^{56}Ni in excess of that produced in non-GRB Type-Ibc SNe is indeed required in some cases (see [53]) there are two ways in which it might be produced by proto-magnetars: (1) some of the initial rotational energy of the core may be tapped rapidly via magnetic stresses, enhancing the SN shock energy as it is launched [43, 54] and/or (2) as the initial slow SN shockwave is moving outward it is shocked by the subsequent, highly-energetic proto-magnetar wind, again enhancing the shock energy [7]. Depending on the angular distribution of the wind kinetic energy, the latter option requires that $\gtrsim 10^{51}$ ergs is extracted from the proto-magnetar on a $\lesssim 1 - 2$ s timescale (see Ref [28, 14]).

Proto-magnetars (and their GRBs) may also be formed by the accretion-induced collapse (AIC) of white dwarfs and (perhaps) by the merger of white dwarfs. In this scenario there is no explosive nucleosynthesis, and perhaps little ^{56}Ni yield [9, 10]. A

standard SN is not expected to accompany AIC due to the low total ejecta mass and modest quantity of radioactive ejecta [55]. However, Ref [56] show that the yield of ^{56}Ni in AIC is significantly enhanced in the case of rapid rotation due to winds from the accretion disk that forms around the neutron star. The radioactive decay of the ejecta produces an optical transient that is somewhat dimmer and evolves much faster (on a timescale ~ 1 day) than a normal SN [56, 57], but which could in principle be detected with rapid and deep follow-up of a nearby event. Ref [58] predict that magnetar formation via AIC ejects up to $\sim 0.1M_{\odot}$ in highly neutron-rich material. The heavy r-process elements produced in such ejecta contribute a comparable amount of radioactive heating to ^{56}Ni on timescales ~ 1 day [59] and thus may also contribute to SN-like emission following the GRB.

Importantly, if proto-magnetar-driven GRBs can arise from AIC, then long-duration GRBs could trace both young and old stellar populations. This is qualitatively different from the collapsar model.

Does Magnetar Birth Always Produce a GRB?

No. Estimates suggest that $\sim 10\%$ of all core-collapse SNe produce magnetars [60]. Thus, the magnetar birth rate likely significantly exceeds the beaming-corrected GRB rate [61]. There are at least four possibilities for relieving this potential tension: (1) many magnetars are born slowly rotating and thus do not produce GRBs, (2) many millisecond magnetars are born in Type-II progenitors with extended hydrogen envelopes and their jets are quenched [62], (3) many millisecond magnetars simply do not form jets able to escape the star (because of, e.g., instabilities), and finally (4) (a variant on the first), because \dot{E} (e.g., eq. 3) is a very strong function of both B and Ω , only the magnetars born at the extremes of these distributions (e.g., $B \gtrsim 10^{15.5}$ G, $P \lesssim 2$ ms) produce bright cosmological GRBs. The rest give rise to less energetic events like XRFs or normal SNe.

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